SECURITY INFORMATION

~~RESTRICTED~~

UNAVAILABLE

RM E52D16

NACA RM E52D16

CONFIDENTIAL

NACA

RESEARCH MEMORANDUM

AN ANALYSIS OF AXIAL- AND CENTRIFUGAL-FLOW TURBOJET-ENGINE PERFORMANCE WITH VARIABLE-AREA EXHAUST NOZZLE

By Zelmar Barson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

~~CLASSIFICATION CHANGED~~

~~To Confidential~~

~~By authority of J.W. Crowley Date 12/1/53~~

naca rel. fm. #1614 ... 12/10/53

CLASSIFIED DOCUMENT

CLASSIFICATION CHANGED

UNCLASSIFIED UNAVAILABLE

To

By authority of Naca ... Effective Date 4-5-57

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

June 19, 1952

CONFIDENTIAL

INFORMATION

~~RESTRICTED~~

UNAVAILABLE

[redacted]
SECURITY INFORMATION

2521

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

AN ANALYSIS OF AXIAL- AND CENTRIFUGAL-FLOW TURBOJET-ENGINE PERFORMANCE WITH VARIABLE-AREA EXHAUST NOZZLE

By Zelmar Barson

SUMMARY

A current turbojet engine of the axial-flow type and one of the centrifugal-flow type were operated at simulated altitude conditions for the purpose of obtaining component performance. Plots of these performance data were then used as the basis for a cycle analysis of the effect on engine performance of a variable-area exhaust nozzle. Calculations were made for both of the basic engines, as well as for similar hypothetical engines having, in turn, higher component efficiencies, higher compressor-pressure ratios, and higher allowable turbine-inlet temperatures.

In every case, the most economical method found for operating the axial-flow engine at a given thrust level was to maintain an engine speed near the rated value and to adjust the area of a variable-area nozzle; however, it was found for the centrifugal engine that no improvement in fuel economy was obtained by the use of a variable-area nozzle. The amount of fuel saved by modulating thrust with a variable-area nozzle over operation with a fixed-area nozzle at reduced engine speeds on the axial-flow engine was 3 or 4 percent, in general, and ran as high as 8 percent for a hypothetical engine having greatly improved component performance.

INTRODUCTION

The extreme range of altitudes and flight speeds to which modern turbojet engines are subjected presents the problem of obtaining efficient engine performance over a wide range of engine-inlet conditions. With a fixed-area exhaust nozzle, optimum performance is not obtained at all flight speeds and altitudes because of changes in the performance of various engine components, notably the compressor, with different ambient conditions. A variable-area exhaust nozzle allows the engine speed and thrust to be varied independently of each other within the temperature limits of the engine, and therefore the most economical method of operation may be selected at any desired thrust. This is true whether engine conditions change because of changing altitude and flight speed or because of other reasons, such as intermittent extraction of auxiliary power from the engine. In addition to possible improvements in fuel economy, a variable-area exhaust nozzle provides a very rapid means of changing engine thrust. This is a highly desirable characteristic for certain military purposes, such as fighter maneuvers and carrier wave-off.

Most previous investigations of turbojet-engine performance with variable-area exhaust nozzles have been confined to one particular engine, and the purpose has been either to evaluate the performance of the nozzle itself or to compare the performance of a particular engine with fixed- and variable-area nozzles. The purpose of this report is to compare the effect on engine performance of the variable-area exhaust nozzle for axial- and centrifugal-flow turbojet engines. The comparison utilizes component performance obtained from a current engine of each type, as well as performance computed on the basis of possible future design practice. The experimental data were obtained in an altitude test chamber at the NACA Lewis laboratory. The range of conditions simulated include a flight Mach number of 0.62 at altitudes of 30,000 and 50,000 feet and a flight Mach number of 0.91 at an altitude of 30,000 feet. The comparisons of present and possible future performance were made at a flight Mach number of 0.62 at an altitude of 30,000 feet.

APPARATUS AND PROCEDURE

The two turbojet engines used in this investigation had similar static-thrust ratings of approximately 5000 pounds and were selected as representative of the two basic types of turbojet engine in current use. Engine A had an 11-stage axial-flow compressor, and engine B had a double-entry centrifugal compressor. Both had multiple-can-type combustion chambers and single-stage reaction turbines.

Engine A was operated in the altitude chamber at simulated altitudes of 30,000 and 50,000 feet at two ram-pressure ratios, 1.30 and 1.70 (corresponding to simulated flight Mach numbers of 0.62 and 0.91, respectively). Both the inlet pressure and temperature were simulated for each condition, assuming 100 percent ram-pressure recovery. A clamshell-type variable-area exhaust nozzle was used, and the exhaust-nozzle area was varied at each of several different engine speeds from its fully open position to either the size necessary to raise the turbine-inlet temperature to the allowable limit or to the minimum possible nozzle area, whichever occurred first. Engine B was operated at the same two ram-pressure ratios as engine A, but only at an altitude of 30,000 feet. Because a variable-area nozzle was not available at the time of the test, engine B was operated with several fixed-area exhaust nozzles ranging in size from approximately 92 percent of the area of the nozzle supplied by the manufacturer to a straight parallel nozzle having the same area as the engine tail pipe (approximately 138 percent of the area of the manufacturer's nozzle). With each of the fixed-area nozzles, the engine was operated over its full range of engine speed at each flight condition. For the purpose of this analysis, only the engine speed range from 80 percent of rated engine speed to 100 percent of rated speed will be considered, because this includes the entire practical operating range of the engine in flight.

2521

Both of the engines were supplied with sufficient instrumentation at the entrance and exit of each engine component to determine the performance of each component. Engine air flow and fuel consumption were also measured in order to determine combustion efficiency.

ANALYSIS

The experimental data obtained from the simulated-altitude operation of the two engines were used to construct compressor performance maps for each engine at the altitudes investigated. With these maps as a basis, together with the experimentally determined values of combustion-chamber pressure loss, combustion efficiency, and turbine efficiency, calculations were made of engine thrust, specific fuel consumption, and turbine-inlet temperature for a range of exhaust-nozzle areas at each of four engine speeds. The speeds selected were 100, 95, 90, and 80 percent of rated speed. The method of calculation and the equations used are given in appendix B.

In order to investigate the possibility of changes in the effectiveness of a variable-area exhaust nozzle on engines having improved component performance, the computations were repeated for a series of hypothetical engines having, in turn, improved compressor and turbine efficiency, higher compressor pressure ratio, and higher allowable turbine-inlet temperature. In each case, only one of these three variables was assumed to change, with the others remaining equal to their value for the current engine. The method by which this was accomplished is described in appendix C. A final calculation was then made by combining the highest values of all three of these parameters as an indication of what might be expected in the future. The following table summarizes the conditions which were calculated. The figures presented are ratios of the value of the parameter assumed for the particular calculation to the value obtained with the current engine.

Calculation number	Altitude (ft)	Ram-pressure ratio	Compressor- and turbine-efficiency ratio	Compressor-pressure-ratio factor	Allowable turbine-inlet temperature ratio
I	30,000	1.30	1.00	1.00	1.00
II	30,000	1.70	1.00	1.00	1.00
III	[a]50,000	1.30	1.00	1.00	1.00
IV	30,000	1.30	1.05	1.00	1.00
V	30,000	1.30	1.10	1.00	1.00
VI	30,000	1.30	1.00	1.50	1.00
VII	30,000	1.30	1.00	2.00	1.00
VIII	30,000	1.30	1.00	1.00	1.10
IX	30,000	1.30	1.00	1.00	1.20
X	30,000	1.30	1.10	2.00	1.20

[a]This condition was calculated for engine A only, because no data were available for engine B.

2521

Compressor Performance

The performance maps for the axial-flow compressor of engine A are shown in figure 1. Engine operating lines for several constant exhaust-nozzle areas are plotted to indicate the difference between constant- and variable-area operation. In order to facilitate comparison between the two engines, all values except compressor pressure ratio and efficiency are shown as the ratio of the actual value to the value of the variable at the rated corrected engine speed and with the exhaust-nozzle area supplied by the manufacturer. A typical feature of the axial-flow compressor is that it operates in the region where large changes in compressor pressure ratio make very little difference in the mass flow through the compressor at a given engine speed.

The compressor map for the centrifugal-flow compressor of engine B is shown in figure 2. This type of compressor normally operates on the flat portion of the characteristic engine speed curve, where very small changes in pressure ratio cause large changes in the mass flow through the compressor.

The immediate effect of a small reduction in exhaust-nozzle area is to increase the turbine-discharge pressure, because the same mass flow must now pass through a smaller exhaust opening. Because the turbine-inlet nozzles are choked in the range of engine speeds being considered in this analysis, this increase in turbine-discharge pressure results in a reduction in the pressure ratio available for expansion through the turbine. However, the compressor still requires the same amount of power, and therefore the turbine-inlet temperature must be increased to keep the engine running at the same speed. At the higher temperature level, the required enthalpy drop across the turbine can be obtained with a lower expansion pressure ratio, and therefore the turbine-discharge temperature is also increased. The reduction in exhaust-nozzle area has thus increased the tail-pipe pressure as well as the turbine-inlet and turbine-discharge temperatures, and the engine now requires a greater fuel flow to maintain its original speed.

From continuity considerations, the increase in turbine-inlet temperature causes a reduction in the mass flow of gas through the turbine. When this reduction in mass flow is felt by the compressor, it will seek a new operating point on its characteristic curve; and since the engine speed is assumed to remain constant, the compressor must follow that line on the map. The axial-flow compressor thus moves to a considerably higher pressure ratio. In this way, the engine will find a new matching point on the compressor map, and the point will occur at a higher pressure ratio than the original condition. The centrifugal compressor, however, absorbs the small reduction in mass flow with no appreciable change in pressure ratio. Inasmuch as the cycle efficiency of a turbojet engine changes as the pressure level of the cycle is varied, the performance of the axial-flow engine should be affected to a greater extent by varying exhaust-nozzle area than will the performance of the centrifugal-flow engine.

Performance of Other Engine Components

The combustor and the turbine performance of the two engines used in this investigation were very similar. The combustor pressure loss was approximately 5 percent of the combustor-inlet total pressure, and the combustion efficiency varied from about 80 to 98 percent for both engines, depending on the engine speed and the simulated flight condition. Turbine efficiency was almost identical for the two engines and remained nearly constant at about 79 percent throughout the range of engine speeds and ram ratios investigated at the 30,000-foot altitude. However, the turbine efficiencies of the axial-flow engine varied somewhat with corrected engine speed at a simulated flight Mach number of 0.62 at 50,000 feet as follows:

Corrected engine speed, percent of rated rpm	Turbine efficiency, percent
109	77.8
104	78.4
96	77.8
86	75.4

The coefficients used in calculating the exhaust-nozzle areas were determined from continuity measurements through the nozzles.

RESULTS AND DISCUSSION

To show the effect of exhaust-nozzle area on the variation of specific fuel consumption with net thrust, data are presented in figures 3(a) and 3(b) for the two engines at a simulated flight Mach number of 0.62 at an altitude of 30,000 feet. The curves represent performance with a constant effective exhaust-nozzle area, and the symbols represent points of constant engine speed as noted. In each of the remaining figures, the standard exhaust-nozzle area is defined as that effective nozzle area which yields the limiting turbine-inlet temperature at rated engine speed for the particular engine and flight condition. The particular areas noted on the figures are effective areas c_dA to permit application of the results to any nozzle of known performance. It can be seen on the figures that the line of limiting turbine-inlet temperature passes through the rated-engine-speed point on the standard-nozzle-area curve. Nozzles smaller than standard are therefore temperature-limited, while nozzles larger than standard are speed-limited, by definition of the standard nozzle. The plot for the axial-flow engine (fig. 3(a)) shows that the envelope of minimum specific fuel consumption for any desired thrust can be obtained by using a nozzle which can be varied from the standard area to approximately 104 percent of standard area.

At thrusts above 70 percent of the normal thrust (with standard nozzle at rated engine speed), the standard nozzle gives within 1 percent the same specific fuel consumption as the most economical nozzle, but at thrusts below 70 percent, the larger nozzles do conserve fuel at a given thrust. At 60 percent of normal thrust, the saving is about 4 percent, and at lower thrusts, the savings become much greater. This represents an appreciable increase in range for a plane such as a multiengined bomber which can cruise on a small percentage of full power.

The same type of plot for centrifugal-flow engine B is shown in figure 3(b). For this type of engine, one particular exhaust-nozzle area, if chosen correctly for the flight condition, will maintain very nearly the minimum specific fuel consumption over the entire range of engine operation from normal thrust to less than 40 percent of normal thrust. For a flight Mach number of 0.62 at an altitude of 30,000 feet, the standard nozzle appears best except for a very small region between normal thrust and about 92 percent of normal thrust, where a slightly larger nozzle shows a small advantage. The reason for the occurrence of best fuel economy at nozzle areas about standard or slightly larger lies in the shape of the compressor performance map. For the centrifugal-flow engine, a decrease in nozzle area from about standard size results in a decreased mass flow without any appreciable increase in compressor pressure ratio. Because thrust is a direct function of mass flow and jet velocity, and jet velocity at a given total pressure is proportional to the square root of the tail-pipe temperature, it is much more economical to obtain a given thrust by keeping the mass flow high at reduced temperature than by raising the temperature at reduced mass flow. This process is, of course, limited to nozzle sizes on the flat portion of the constant-speed line before pressure ratio drops off. The centrifugal engine does not have the advantage of the axial-flow engine that a decreased nozzle area raises the compressor pressure ratio and therefore the cycle efficiency.

2521

At a simulated flight Mach number of 0.91 at an altitude of 30,000 feet, neither engine shows any appreciable advantage for the variable-area exhaust nozzle (figs. 3(c) and 3(d)). Any fixed-area nozzle from standard to about 104 percent of standard area will maintain the minimum specific fuel consumption for either engine throughout the range of engine speeds investigated. The difference between the results of figures 3(a) and 3(c) is probably due to the higher pressure level of the engine when operating at the higher flight Mach number. The small change in pressure ratio caused by a change in exhaust-nozzle area therefore represents a smaller percentage change in the cycle efficiency of the engine and so is less apparent in terms of specific fuel consumption. It should also be noted that at higher flight speeds, with resulting higher engine-inlet temperature, the engine is operating at lower corrected engine speed; in that region the change in compressor efficiency with a given change in nozzle size is less than at higher engine speeds.

The effectiveness of a variable-area nozzle at high altitude is presented in figure 3(e) for the axial-flow engine. At a simulated flight Mach number of 0.62 and an altitude of 50,000 feet, a variable-area nozzle becomes more effective than at lower altitudes. In order to follow the envelope curve of minimum specific fuel consumption here, it is necessary to vary the nozzle area from standard to at least 108 percent of standard area. At 50 percent of normal thrust, the 108-percent nozzle represents a saving of 5 percent of the engine fuel over operation with the standard nozzle. The portions of the curves extending to the right of the limiting-turbine-inlet-temperature line were extrapolated during the computational process and should be correct if the turbine-inlet temperature were allowed to go higher. In that case, nozzle areas smaller than standard would also be needed to maintain best fuel economy, as the constant-nozzle-area lines turn sharply upward after reaching their minimum value.

The greater advantage of the variable-area nozzle at high altitude results from the fact that the constant-area-nozzle specific-fuel-consumption curves rise more rapidly from the minimum with either an increase or decrease in net thrust. This greater sensitivity of the specific fuel consumption to net thrust or engine speed is a result of more rapid changes in compressor, turbine, and conbustion efficiencies at the higher altitude with changes in engine speed. Because the necessary change in engine speed to effect a given change in thrust has a more detrimental effect on component efficiencies than the required change in nozzle area, it is somewhat more economical to decrease thrust by opening the exhaust nozzle than by decreasing engine speed.

Effect on Engines Having Improved Component Performance

The foregoing figures indicate that with present-day engine performance there is not very much to be gained in economy by using a variable-area exhaust nozzle except at very low thrust levels or at high altitudes. However, the design of engines is constantly being changed for improved performance, and it is therefore necessary to investigate the effect of a variable-area exhaust nozzle on engines incorporating probable future design practices.

As has been previously mentioned in the section ANALYSIS, calculations were made of the performance of hypothetical engines having similar compressor maps to engines A and B, but each differing in one respect. Compressor and turbine efficiency, compressor pressure ratio, and allowable turbine-inlet temperature were each increased in turn, and all other factors were held constant; a final calculation was then made in which the highest value of all three parameters was used. The method in which these parameters were varied is explained in appendix C. A simulated flight Mach number of 0.62 at an altitude of 30,000 feet was used for all of the remaining calculations and figures.

Effect with higher component efficiencies. - The effect of a variable-area exhaust nozzle on the performance of engines having higher compressor and turbine efficiencies is shown in figure 4. The calculations for figure 4 were made from the compressor maps of figures 1(a) and 2, except that each efficiency value was multiplied by 1.05 for figures 4(a) and 4(b) and by 1.10 for figures 4(c) and 4(d). The top value of 1.10 was chosen as a reasonable limit to what might be expected in compressor performance in the near future. A comparison of the results for the two engine types is similar to that for the standard engine at this flight condition. The axial-flow engine shows savings in fuel ranging up to 4 percent at thrusts between normal and 50 percent of normal. The centrifugal-flow engine again shows practically no advantage for the variable-area nozzle at any one flight condition. Fuel savings of perhaps 1 or $1\frac{1}{2}$ percent are possible. A fixed nozzle of 104 percent standard area would be optimum for the conditions of figure 4(b) and any nozzle from 108 to 116 percent of standard area would be equally good for an engine with still higher component efficiencies. It must be remembered, however, that any nozzle larger than standard will not allow the engine to operate at rated thrust. The very slight improvement in effect of the variable-area nozzle for both engines is explained by the fact that a given change in exhaust-nozzle area now results in a 5 or 10 percent greater change in compressor efficiency. The lower losses caused by the improved turbine efficiency also have a favorable effect on variable-area-nozzle performance.

<u>Effect with increased compressor pressure ratio</u>. - The data for figure 5 were calculated from the compressor maps of figures 1(a) and 2 with the compressor-pressure-ratio values multiplied by 1.5 and 2.0, respectively. It can be seen that for the axial-flow engine the savings in fuel which can be achieved are smaller than in the previous cases and that at the highest pressure ratio (fig. 5(c)) the savings are almost zero over operation with the standard nozzle area. This is attributable to the fact that at the higher pressure level of operation, the cycle efficiency of the engine is already so high that small changes in pressure level cause very small changes in performance. It should be noted, however, that in this analysis exact similarity of the compressor maps is assumed for the basic engine and for the high-pressure-ratio engines. This is not necessarily the case; because the effect of the variable-area nozzle on engine performance has been shown to depend on the detailed shape of the characteristic compressor curves, the performance of the high-pressure-ratio engines may be quite different from that which is presented here. For the centrifugal-flow engine (figs. 5(b) and 5(d)) there is again no advantage for the variable-area nozzle, as fixed-area nozzles of 96 and 92 percent of standard area, respectively, follow very nearly the envelope of minimum specific fuel consumption.

<u>Effect with higher allowable turbine-inlet temperature</u>. - The allowable turbine-inlet gas temperature imposes a definite limit on turbojet-engine operation because of loss of strength of the materials in the high-temperature region, especially in the turbine blading. Current research, however, is directed toward operation with higher gas temperatures, and it will therefore be useful to know what may be expected from a variable-area exhaust nozzle under these conditions. The performance calculations were therefore repeated; the compressor maps of figures 1(a) and 2 were used as before, and the turbine-nozzle area was adjusted to give turbine-inlet gas temperatures of 1.1 and 1.2 times the present limit of about 2000° R in figures 6(a) and 6(b), and 6(c) and 6(d), respectively.

For the axial-flow engine (figs. 6(a) and 6(c)), it can again be seen that fuel savings up to about 3 percent can be obtained at thrusts between 50 and 80 percent of normal by use of a variable-area exhaust nozzle. For the centrifugal-flow engine, there is again no advantage over operation with a fixed-area nozzle (figs. 6(b) and 6(d)). The increased savings in fuel over operation with the standard-axial-engine configuration are again due to the fact that at the higher temperature level of operation the changes in performance caused by variations in exhaust-nozzle area are more pronounced.

<u>Effect with combined component improvements</u>. - In order to investigate the effect of a variable-area exhaust nozzle on engines having

all of the foregoing improvements, a final set of calculations was made in which the highest values of all three parameters were used. That is, the values of compressor and turbine efficiency were each multiplied by 1.10, the compressor pressure ratios were multiplied by 2.0, and an allowable turbine-inlet temperature of 2400° R (1.2 times normal) was used. The data resulting from these calculations are presented in figure 7. It can be seen that the small (2 to 4 percent) improvements in fuel economy caused by each of the variables separately are approximately additive, and at 60 percent of normal thrust a variable-area nozzle used on an axial-flow engine with these characteristics will 2521
result in fuel savings as high as about 8 percent over operation with the standard nozzle (fig. 7(a)). For the centrifugal-flow engine, as might be expected, a single fixed-area nozzle of rather large size (about 120 percent of standard area) will again follow the minimum-specific-fuel-consumption curve at any given thrust (fig. 7(b)). However, the maximum thrust obtainable with this large nozzle area without exceeding allowable turbine-inlet temperatures is only about 85 percent of normal thrust, and, therefore, it would be necessary to use at least a two-position nozzle if it were desired to operate over the full range of engine thrust.

CONCLUDING REMARKS

The results of an analytical investigation of engine performance with a variable-area exhaust nozzle for typical current axial- and centrifugal-flow turbojet engines indicated that there is little to be gained in fuel economy by use of a variable-area exhaust nozzle on current engines. It is indicated that the axial-flow engine can be operated more economically with a variable-area nozzle than with any single fixed-area nozzle only at thrusts below about 70 percent of normal thrust as savings at the higher thrust values are very small. The centrifugal-flow-engine calculations indicated that no savings in fuel are possible over operation with a fixed-area nozzle of the proper size for any given flight condition.

It is indicated, however, that for future axial-flow engines of improved component performance, there are definite gains to be achieved in fuel economy by the use of a variable-area exhaust nozzle over operation with any single fixed-area nozzle. The savings in fuel obtained by the use of a variable-area exhaust nozzle increased somewhat for engines having higher compressor and turbine efficiency or higher allowable turbine-inlet temperature. Although the advantage decreased slightly for engines having higher compressor pressure ratios at present-day component efficiencies, it is indicated that for more efficient engines operating at higher temperature levels, higher pressure ratios add to the fuel savings. The small (3 or 4 percent) savings in fuel accomplished by the variable-area exhaust nozzle on engines having

any one of the previously discussed design improvements were approximately additive, so that for an engine having a combination of these improvements, greater savings can be expected. On a hypothetical engine having twice the pressure ratio of the axial-flow engine used in this investigation, as well as compressor and turbine efficiencies 10 percent higher and an allowable turbine-inlet temperature of 2400° R instead of the current 2000°, fuel savings up to 8 percent are possible at about 50 percent of normal thrust if the thrust is reduced by opening the variable-area nozzle at high engine speed instead of by reducing
2521 the engine speed with the standard nozzle. At higher thrust values, the savings are proportionately less.

In addition, the variable-area nozzle has the advantage of making possible very rapid changes in engine thrust and the removal of intermittent auxiliary power from the engine with maximum efficiency. It should also be noted in passing that most of the new engines now in design or production are being provided with afterburners, and this in itself requires that the engine be provided with at least a two-position variable-area exhaust nozzle. The addition of a control which would permit continuous nozzle-area variation in this range, therefore, is all that is required to achieve the aforementioned advantages in engine performance.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

APPENDIX A

SYMBOLS

A	area, sq ft
c_d	exhaust-nozzle discharge coefficient
F	thrust, lb 2521
f	fuel-air ratio
g	acceleration of gravity, 32.17 ft/sec^2
H	enthalpy based on total temperature, Btu/lb
h_f	lower heating value of fuel, Btu/lb
K	burner total-pressure loss factor, turbine-inlet total pressure divided by compressor-discharge total pressure
M	Mach number
m	mass flow, slugs/sec
N	engine speed, rpm
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant, 53.35 ft-lb/(lb)($^{\circ}$F)
T	total temperature, $^{\circ}$R
V	velocity, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
γ	ratio of specific heats, c_p/c_v
δ	ratio of compressor-inlet total pressure to NACA standard sea-level pressure, $P_1/2116$

η adiabatic efficiency

θ ratio of compressor-inlet total temperature to NACA standard sea-level temperature, $T_1/518.4$

λ factor accounting for the difference in enthalpy of the carbon dioxide and water in the combustion products and the oxygen used in their formation, Btu/lb

2521

Subscripts:

a air

b burner

c compressor

cr critical

e effective

f fuel

g gas

j jet

n net

t turbine

Station notation:

0 free-stream (ambient)

1 compressor inlet

2 compressor discharge

3 turbine inlet

4 turbine discharge (tail pipe)

5 exhaust-nozzle throat

APPENDIX B

METHOD OF CALCULATION

The compressor maps of figures 1 and 2 were obtained by simulated-altitude operation of the two engines and were used as a basis for all calculations. A series of points representing different exhaust-nozzle areas was arbitrarily chosen at each of several engine speeds on each of the maps. Typical points are shown on the 100-percent-engine-speed line of figure 1(a). The engine speed and the air flow values on the compressor map are corrected to NACA standard sea-level pressure and temperature so that the map will generalize. 2521

The performance calculations were made in the following manner. For each arbitrarily selected point on the compressor map, the values of air flow, pressure ratio, and compressor efficiency were read. The air flow was reduced to the proper value for the altitude and flight speed being considered by application of the δ and θ corrections. With the inlet temperature to the compressor and the compressor pressure ratio and efficiency known, the compressor-discharge temperature T_2 was calculated from the following equation:

$$\eta_c = \frac{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{T_2}{T_1} - 1} \tag{B1}$$

where γ was assumed to be 1.40.

The enthalpy rise across the compressor can now be found from reference 1 by subtracting the tabulated values of enthalpy H at compressor-inlet and -discharge temperatures.

The total-pressure loss in the combustion chamber was obtained from the altitude-performance data and can now be used to determine the turbine-inlet pressure from the relation

$$P_3 = KP_2 \tag{B2}$$

The turbine-inlet nozzle area is known for each engine from the manufacturer's information. In the range of engine speeds being considered in this investigation, it can be assumed that the turbine nozzles are always choked. This fact, together with the known air flow and turbine-inlet pressure, allows the turbine-inlet temperature T_3

to be calculated. If the fuel-air ratio f is assumed as a first approximation, the gas flow through the turbine will be known. The continuity equation for choked flow is

$$W_{g,3} = \frac{P_3 A_3}{\sqrt{T_3}} \sqrt{\frac{g}{R}} \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{B3}$$

2521

where the value of γ is taken for the approximate temperature and the assumed fuel-air ratio in the burner.

Solving this equation for T_3 yields

$$T_3 = \left(\frac{P_3 A_3}{W_{g,3}}\right)^2 \frac{g}{R} \left[\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right] \tag{B4}$$

It can be seen that the temperature is a function only of γ and the known values of pressure, area, and gas flow. If the resultant temperature is then used to find the required fuel-air ratio, this value can be used in equation (B4) as a second approximation to obtain a more accurate temperature. The required fuel-air ratio can be calculated from data obtained previously if the combustion efficiency of the engine combustor is known, and the combustion efficiency was also determined during the altitude-performance operation of the two engines. The required fuel-air ratio is

$$f = \frac{H_3 - H_2}{(\eta_b h_f - \lambda_3)} \tag{B5}$$

where λ is determined from reference 2 at the calculated value of T_3 and enthalpy values are read from reference 1. This iteration for the calculation of T_3 converged very rapidly and usually resulted in a compatible value of the temperature after two computations.

The enthalpy drop of the gas across the turbine must be equal to the enthalpy rise of the air across the compressor, which has already been determined. It is thus possible to find the enthalpy of the tail-pipe gases. It must be remembered that the gas flow through the turbine is greater than the air flow through the compressor by the added fuel. Therefore, on a per-pound basis,

$$(1 + f)(H_3 - H_4) = H_2 - H_1 \tag{B6}$$

The value of turbine efficiency was also determined from the simulated altitude data and was used along with the calculated values of turbine-discharge temperature and turbine-inlet temperature and pressure to find the turbine-discharge pressure.

$$\eta_t = \frac{1 - \frac{T_4}{T_3}}{1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}} \tag{B7}$$

2521

where T_4 was determined from reference 1 at the calculated value of the tail-pipe enthalpy H_4.

With the pressure, temperature, and mass flow in the tail pipe determined, it is possible to calculate the thrust and exhaust-nozzle area. Dimensionless velocity and pressure parameters for one-dimensional flow can be developed as a function of static-to-total pressure ratio in the gas stream. The parameters used in these calculations are:

Velocity parameter:

$$\frac{V}{\sqrt{gRT}} = \left\{\frac{2\gamma}{\gamma-1}\left[1 - \left(\frac{p}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{B8}$$

Static-pressure parameter:

$$\frac{pA}{m\sqrt{gRT}} = \left\{\frac{2\gamma}{\gamma-1}\left[\left(\frac{p}{P}\right)^{\frac{2(1-\gamma)}{\gamma}} - \left(\frac{p}{P}\right)^{\frac{1-\gamma}{\gamma}}\right]\right\}^{-\frac{1}{2}} \tag{B9}$$

Such parameters are tabulated in reference 3 for various values of γ.

The value of γ to be used for any given calculation is determined for the proper tail-pipe temperature and fuel-air ratio.

The velocity parameter used $V_e/\sqrt{gRT}$ involves an effective velocity, which is defined as that velocity which would be attained isentropically by a completely expanded nozzle at the given pressure

[redacted]

ratio. When this parameter is used to calculate the jet thrust, it is unnecessary to add the term $A_5(p_5 - p_0)$ if the proper value of nozzle velocity coefficient is used.

The exhaust-nozzle expansion pressure can be calculated from P_4 and the ambient static pressure p_0 at the altitude being considered. With this pressure ratio and a value of γ selected for the tail-pipe total temperature and the fuel-air ratio, a value of the effective velocity parameter is found from reference 3 and the jet thrust is calculated from the following equation:

2521

$$F_j = mV_e = \frac{W_g}{g}\left(\frac{V_e}{\sqrt{gRT}}\right)_5 \sqrt{gRT_4} \tag{B10}$$

From the previously determined value of γ in the tail pipe, it is possible to determine the critical pressure ratio of the flow and so to determine whether or not the nozzle expansion is choked. The required effective area of the exhaust nozzle to pass the known mass flow at the known pressure and temperature can then be calculated from the proper flow equation. The nozzle velocity coefficient was assumed to be unity. For subcritical flow, the effective nozzle area is

$$c_dA_5 = \frac{W_g}{p_0}\left(\frac{pA}{m\sqrt{gRT}}\right)_5 \sqrt{\frac{RT_4}{g}} \tag{B11}$$

For choked (critical) flow, the effective nozzle area is

$$c_dA_5 = \frac{W_g}{P_4}\left(\frac{P}{p}\right)_{cr}\left(\frac{pA}{m\sqrt{gRT}}\right)_{cr} \sqrt{\frac{RT_4}{g}} \tag{B12}$$

where $(p/P)_{cr}$ and $(pA/m\sqrt{gRT})_{cr}$ are functions of γ only.

The net thrust can now be calculated from the jet thrust by subtracting the momentum of the inlet air at the simulated flight speed and altitude; the specific fuel consumption is calculated from the fuel-air ratio, air flow, and net thrust as follows:

$$F_n = F_j - \frac{W_aV_0}{g} \tag{B13}$$

where

$$V_0 = \sqrt{2gR \frac{\gamma}{\gamma-1} T_1 \left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$\frac{W_f}{F_n} = \frac{3600 \; fW_a}{F_n} \qquad \text{(B14)}$$

2521

APPENDIX C

METHOD OF SELECTING IMPROVED PERFORMANCE PARAMETERS

As was pointed out in the text, it was desired to find the effectiveness of a variable-area exhaust nozzle on engines having certain changes in design aimed at improved performance. In this respect, the three most obvious parameters are compressor and turbine efficiency, 2521 compressor pressure ratio, and maximum turbine-inlet temperature. In order to investigate each of these separately, a series of hypothetical engines was set up, having compressor maps identical to the original engines except for the one parameter being varied.

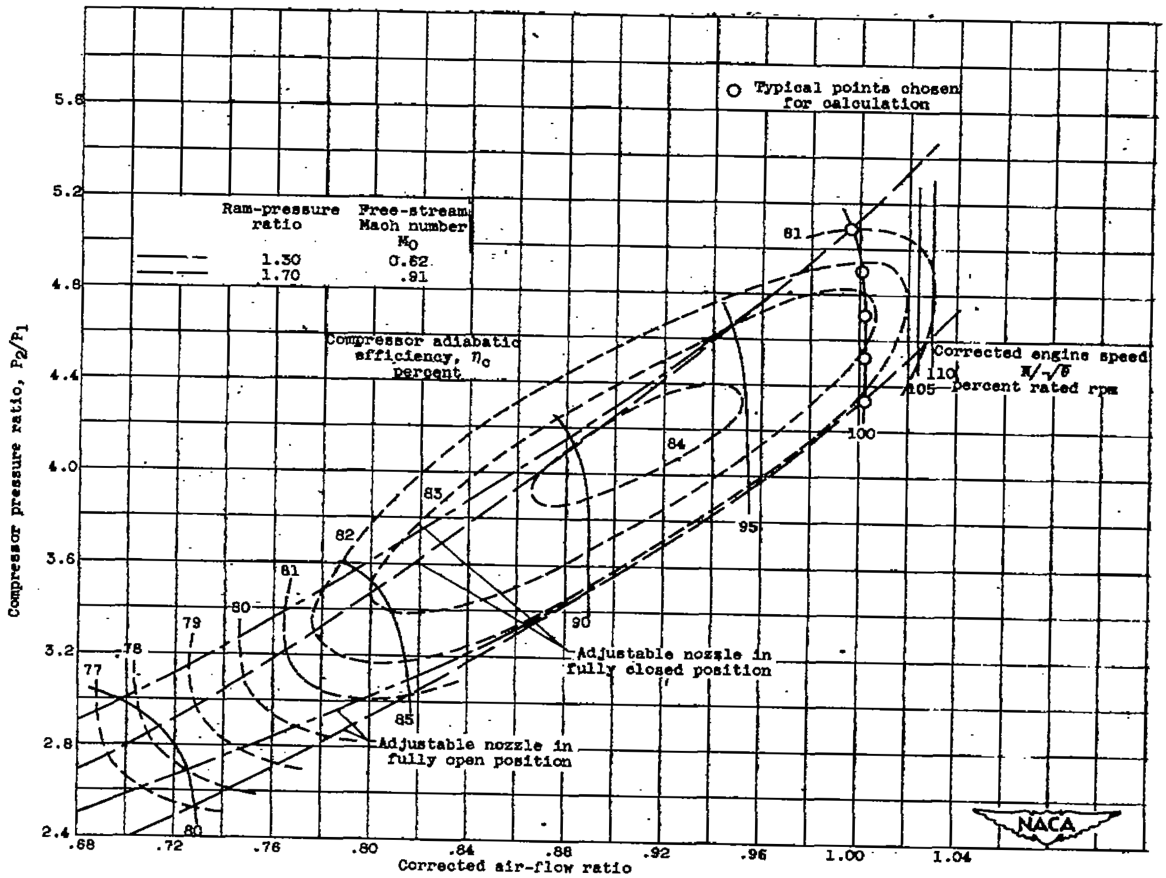
On the basis of data obtained during compressor performance investigations, it was decided that the most rational basis for changing any of the preceding parameters would be to multiply each value of the parameter by a constant after reading it from the original compressor maps. This appears to be more realistic than adding a constant to each value. Thus it was necessary to determine the magnitude of the constant to be used, and this was done so as to make the maximum values of each parameter fall within a range which might reasonably be expected from future engines. The compressor and turbine efficiencies, which reach a maximum value in the region of 80 percent on current engines, were multiplied by 1.05 and 1.10, which would raise the peak value to the vicinity of 90 percent. The compressor pressure ratios, which reach about 5.0, were multiplied by 1.5 and 2.0, which is expected of engines now in design; the allowable turbine-inlet temperature, which is now limited to about 2000° R, was multiplied by 1.1 and 1.2, as material limits will probably be difficult to raise above 2400° R.

REFERENCES

1. Keenan, Joseph H., and Kaye, Joseph: Gas Tables. John Wiley & Sons, Inc., 1948.

2. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

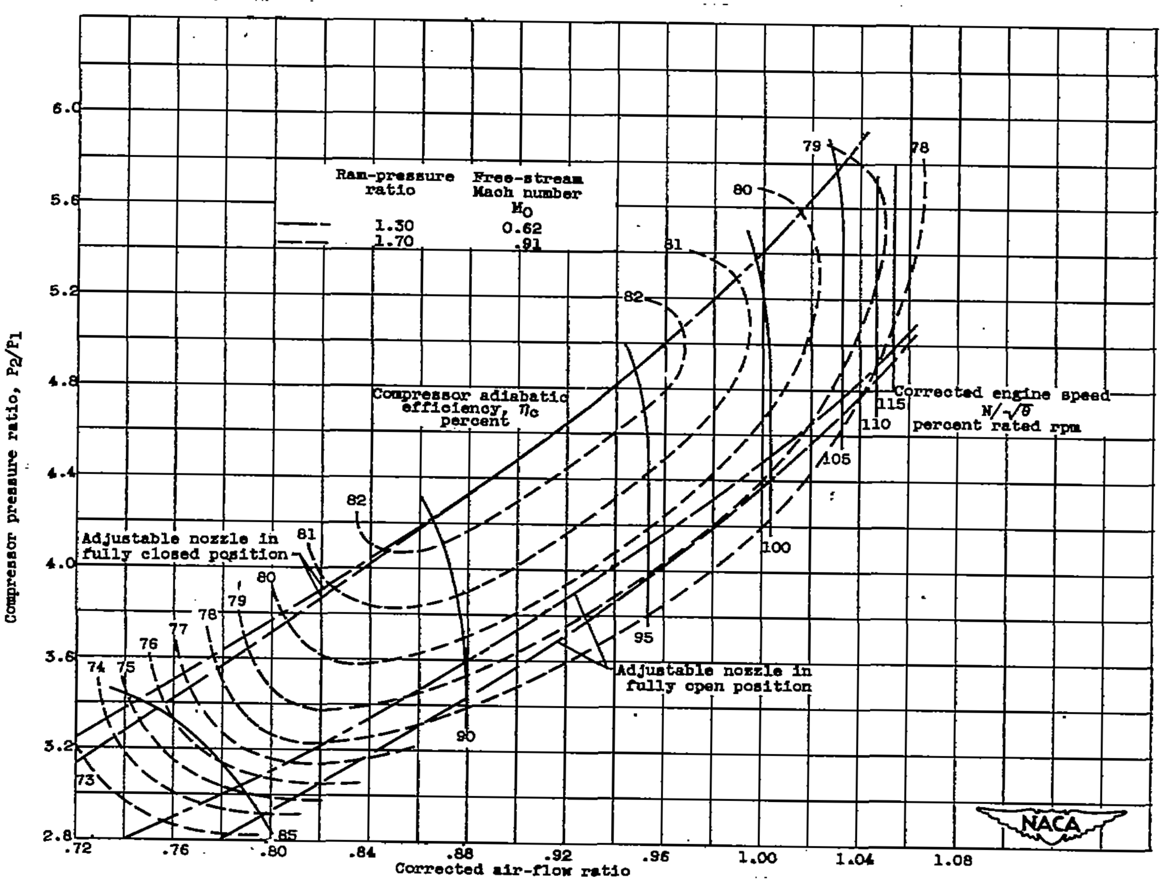
3. Turner, L. Richard, Addie, Albert N., and Zimmerman, Richard H.: Charts for the Analysis of One-Dimensional Steady Compressible Flow. NACA TN 1419, 1948.



(a) Altitude, 30,000 feet.

Figure 1. - Compressor performance maps for axial-flow engine A.

2521



(b) Altitude, 50,000 feet.

Figure 1. - Concluded. Compressor performance maps for axial-flow engine A.

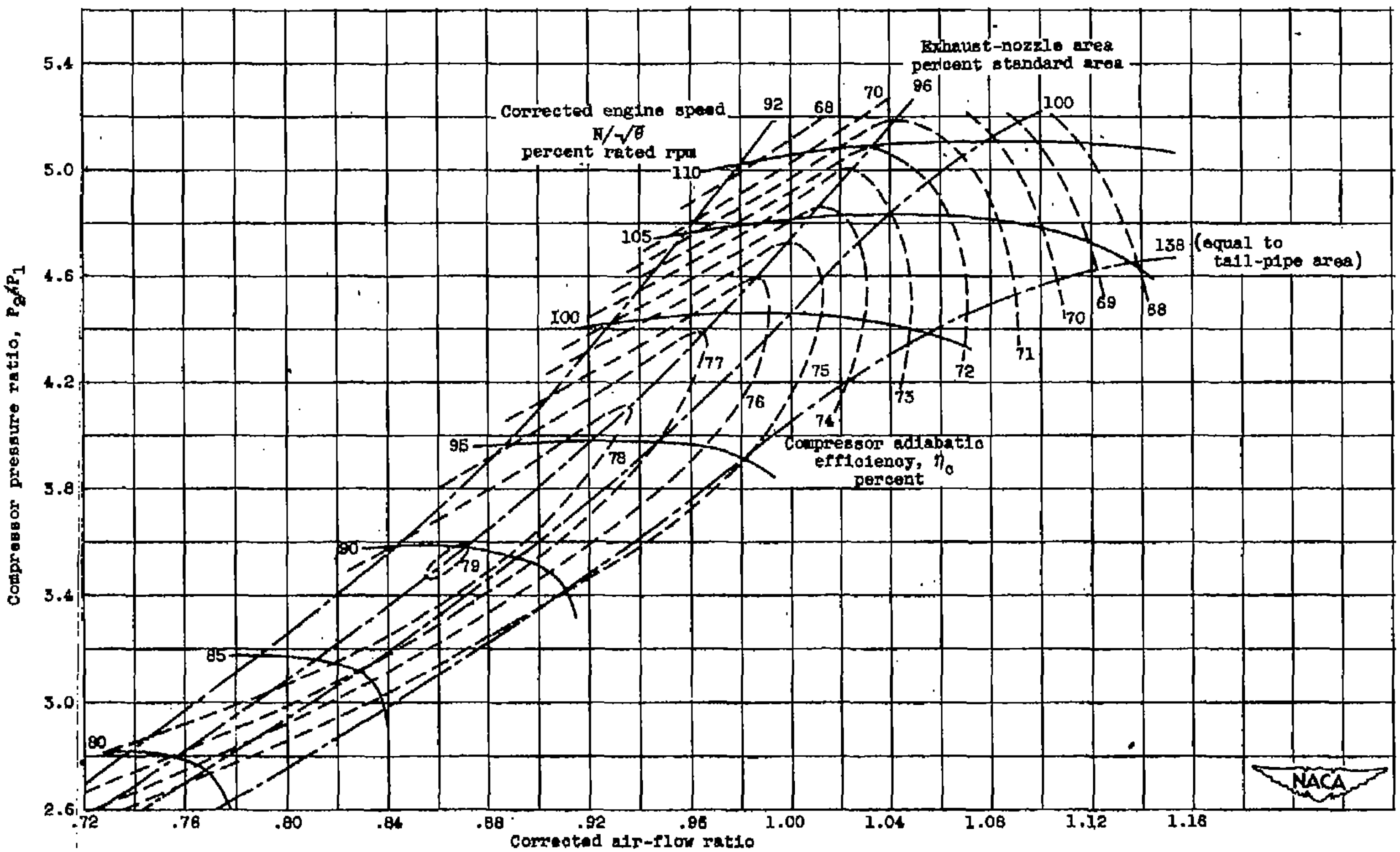
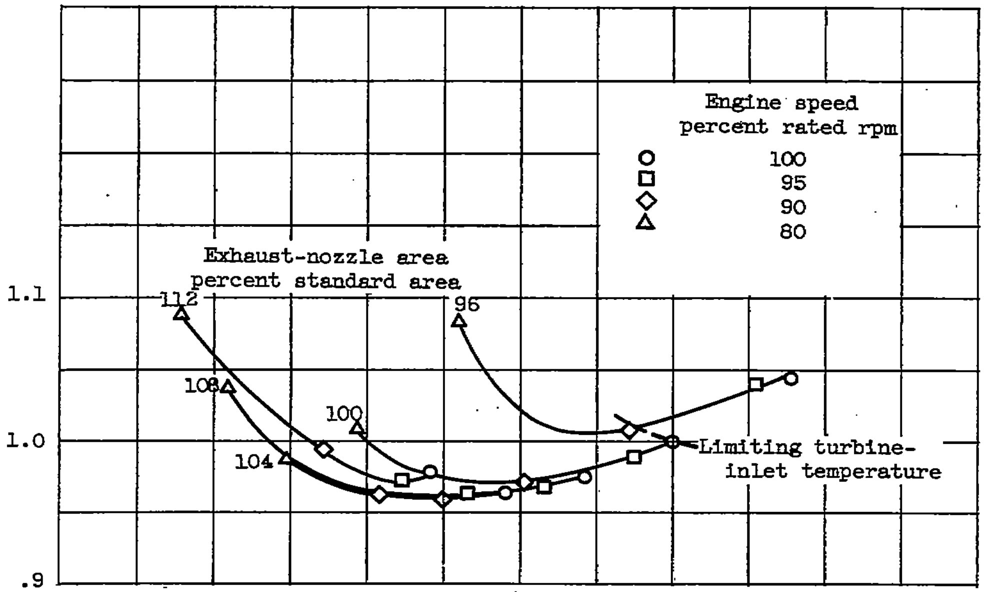
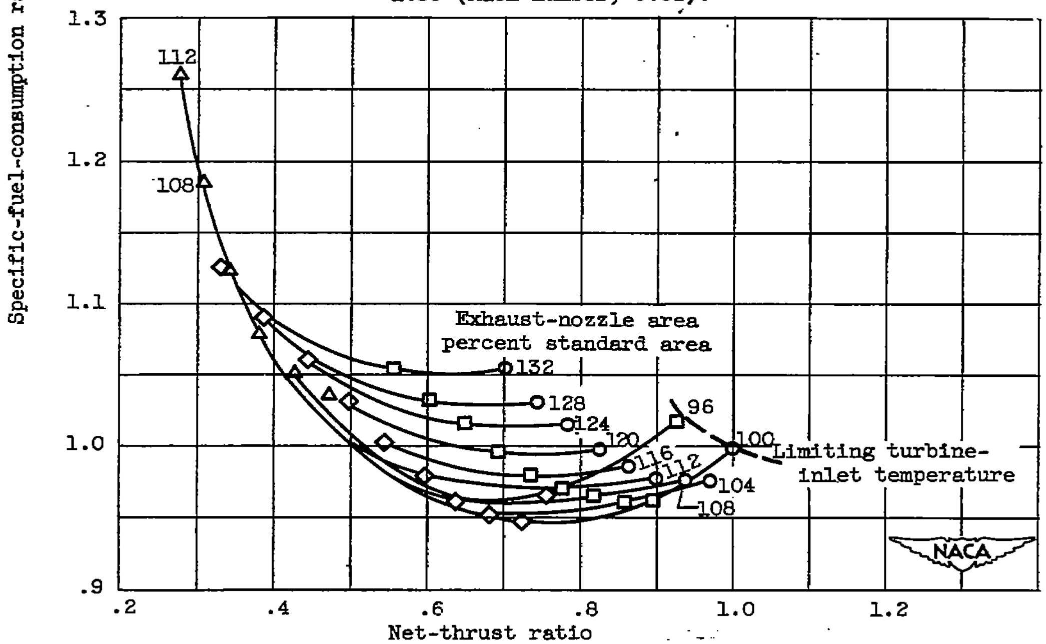


Figure 2. - Compressor performance map for centrifugal-flow engine B. Altitude, 30,000 feet.

2521

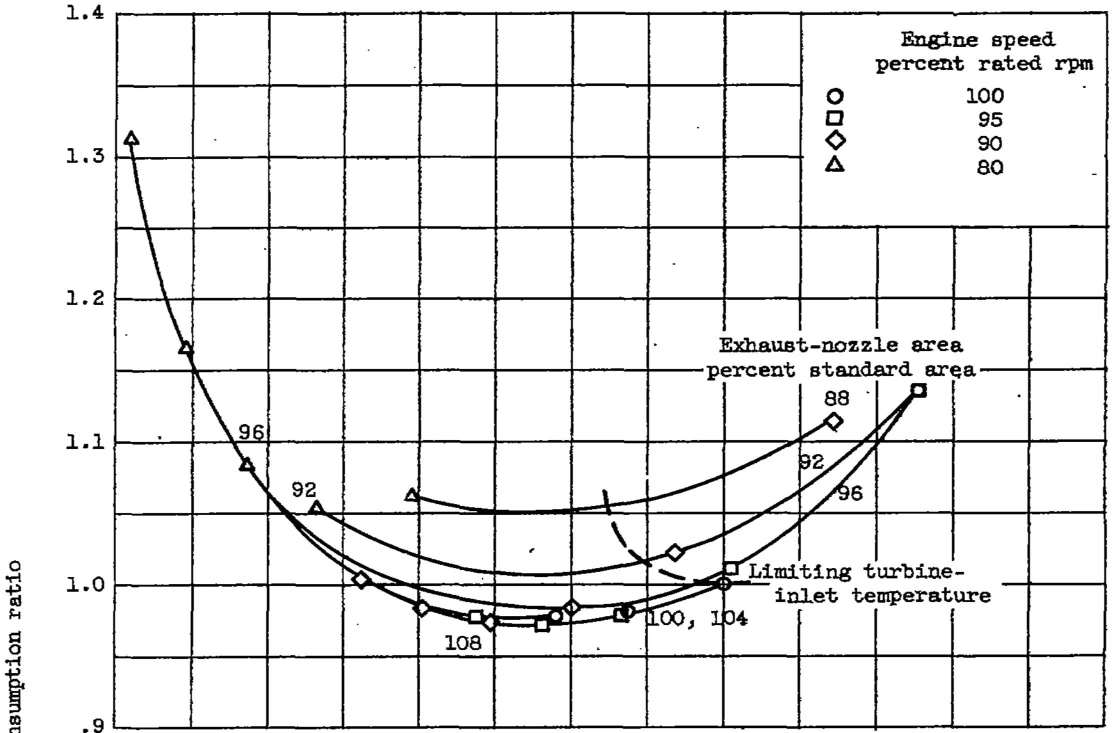


(a) Axial-flow engine A. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

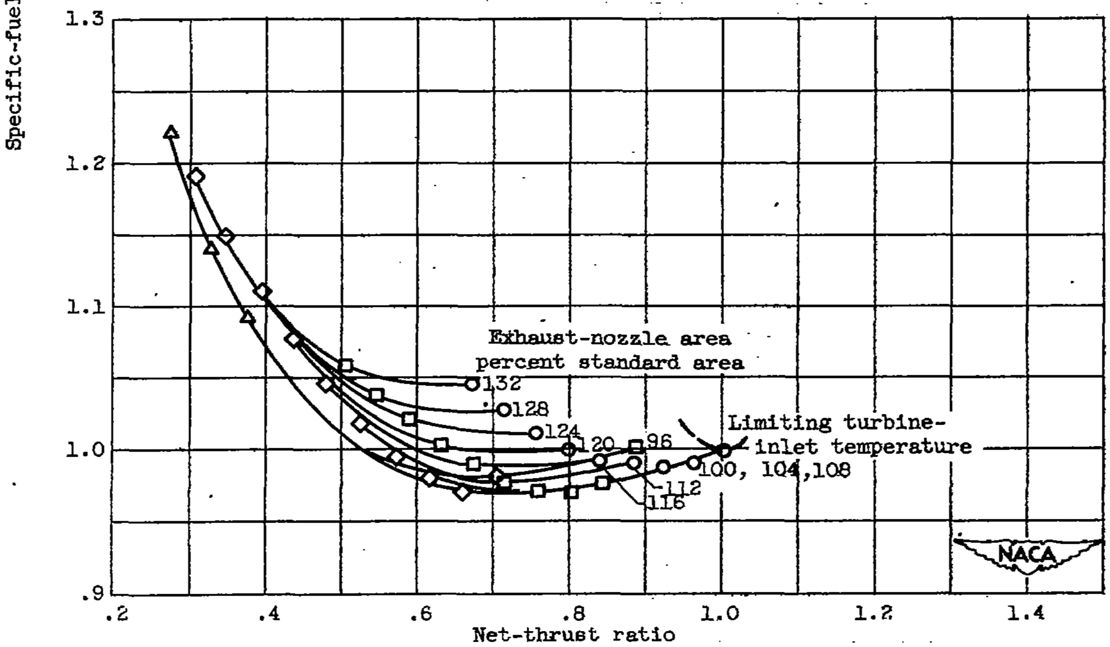


(b) Centrifugal-flow engine B. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

Figure 3. - Effect of variable-area exhaust nozzle on performance of standard engines.



(c) Axial-flow engine A. Altitude, 30,000 feet; ram-pressure ratio, 1.70 (Mach number, 0.91).



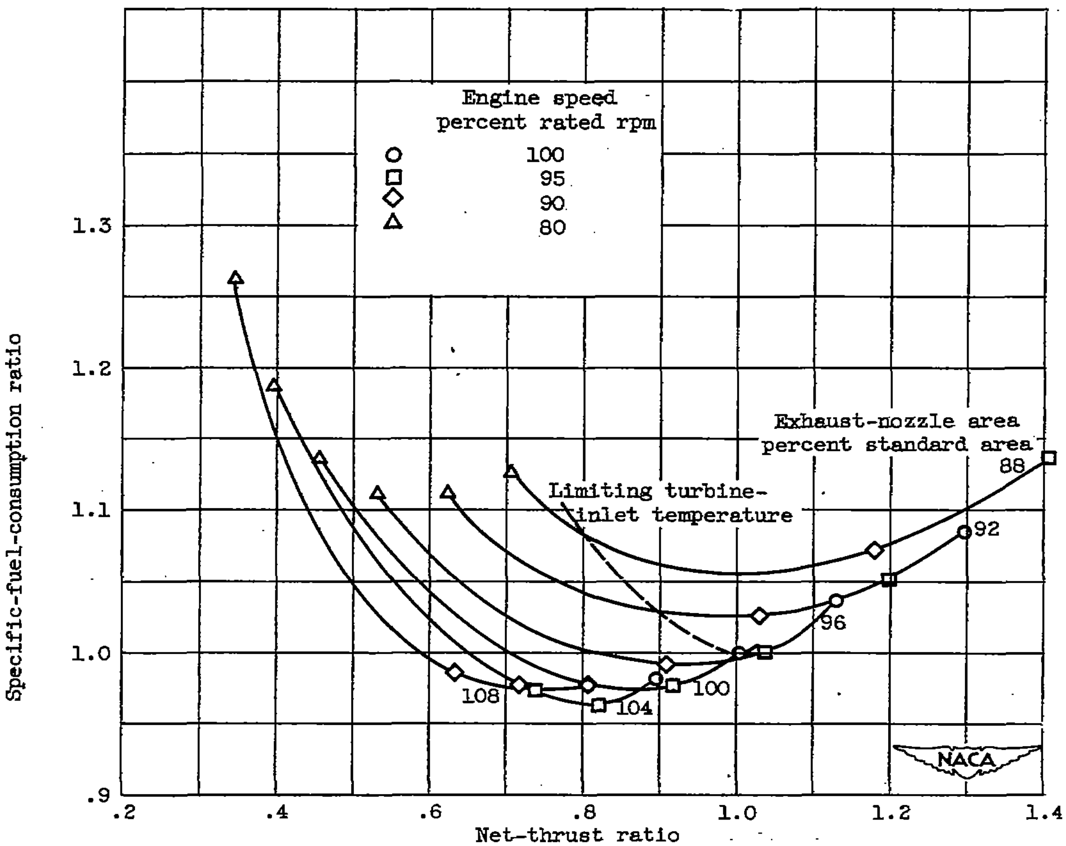
(d) Centrifugal-flow engine B. Altitude, 30,000 feet; ram-pressure ratio, 1.70 (Mach number, 0.91).

Figure 3. - Continued. Effect of variable-area exhaust nozzle on performance of standard engines.

2521

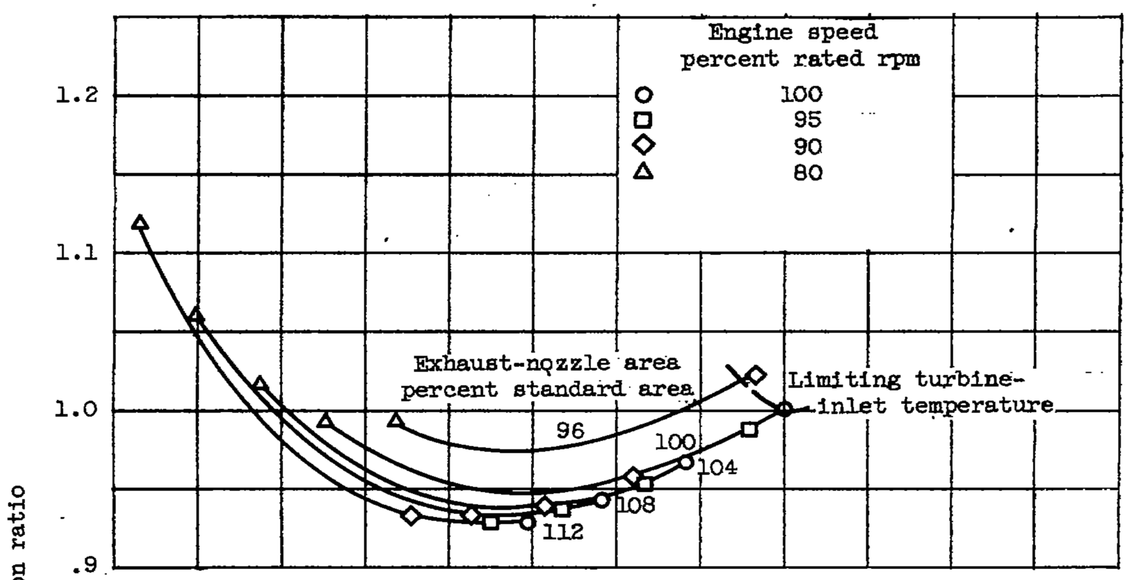
[redacted]

2521

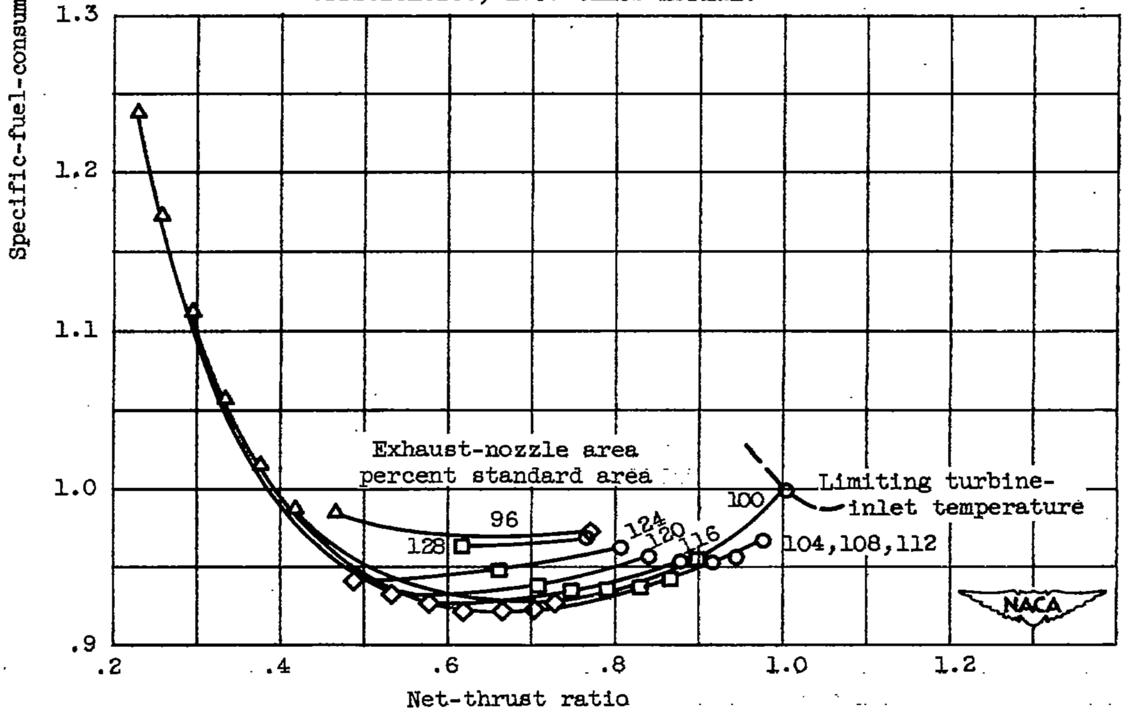


(e) Axial-flow engine A. Altitude, 50,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

Figure 3. - Concluded. Effect of variable-area exhaust nozzle on performance of standard engines.



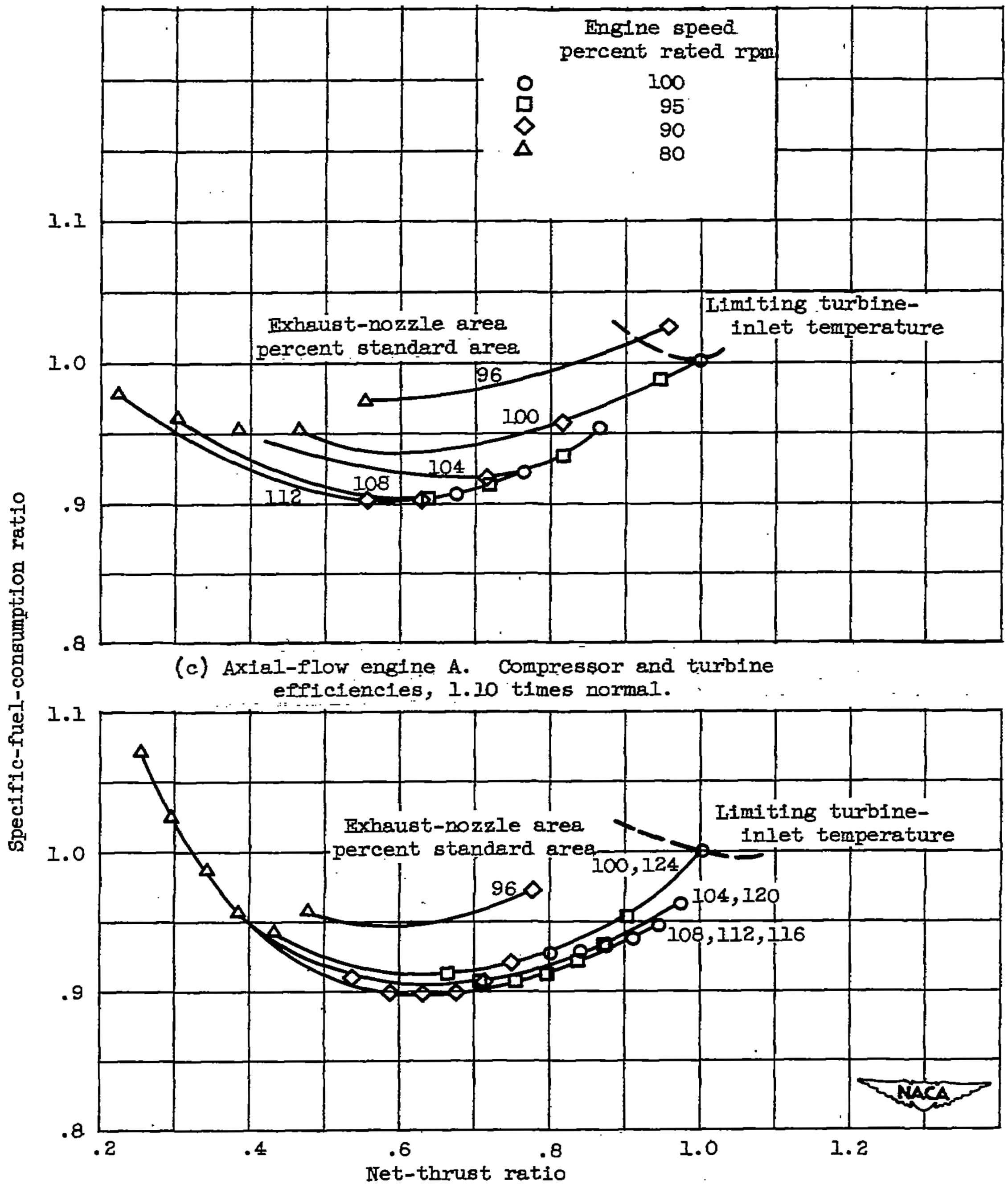
(a) Axial-flow engine A. Compressor and turbine efficiencies, 1.05 times normal.



(b) Centrifugal-flow engine B. Compressor and turbine efficiencies, 1.05 times normal.

Figure 4. - Effect of variable-area exhaust nozzle on performance of engines having improved compressor and turbine efficiency. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

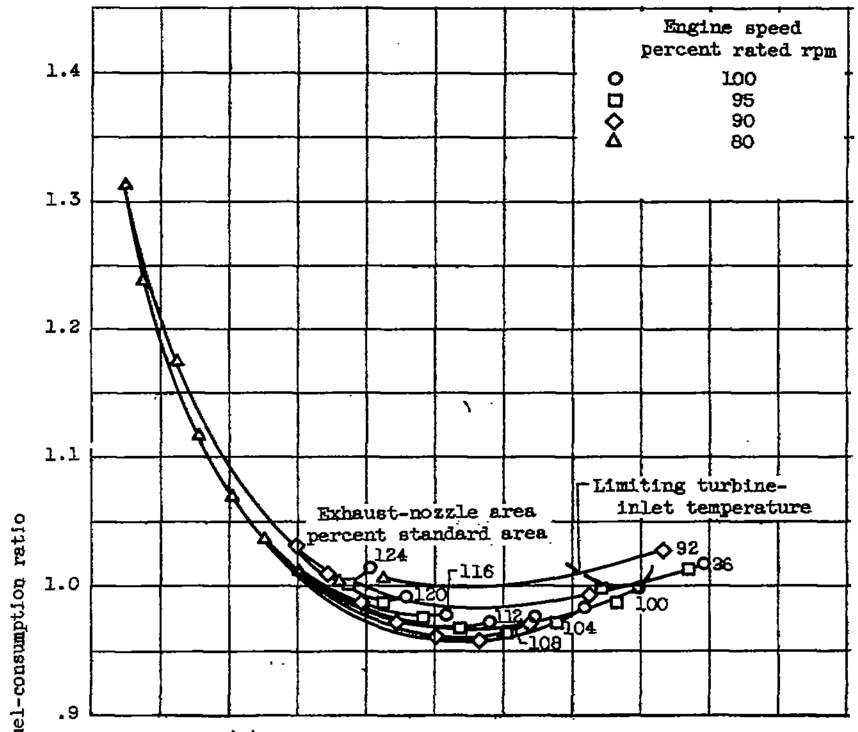
2521



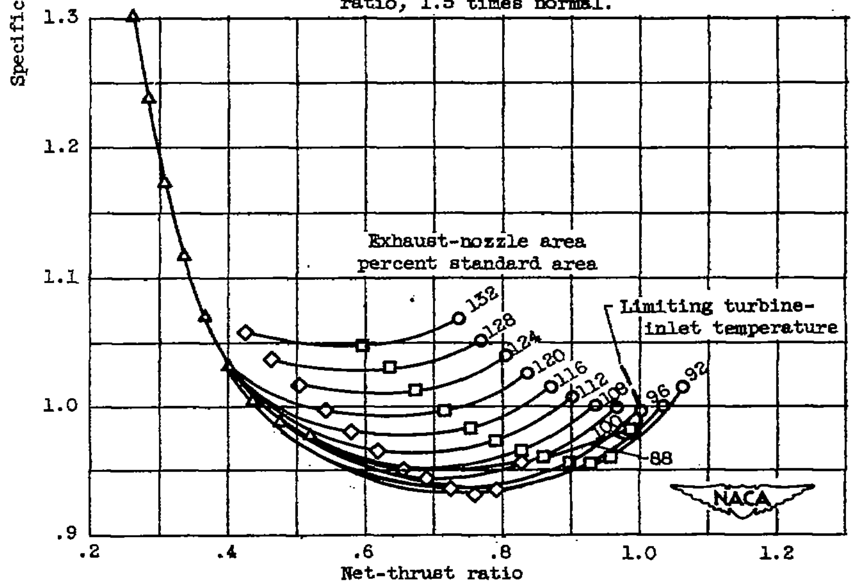
(d) Centrifugal-flow engine B. Compressor and turbine efficiencies, 1.10 times normal.

Figure 4. - Concluded. Effect of variable-area exhaust nozzle on performance of engines having improved compressor and turbine efficiency. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

[redacted]



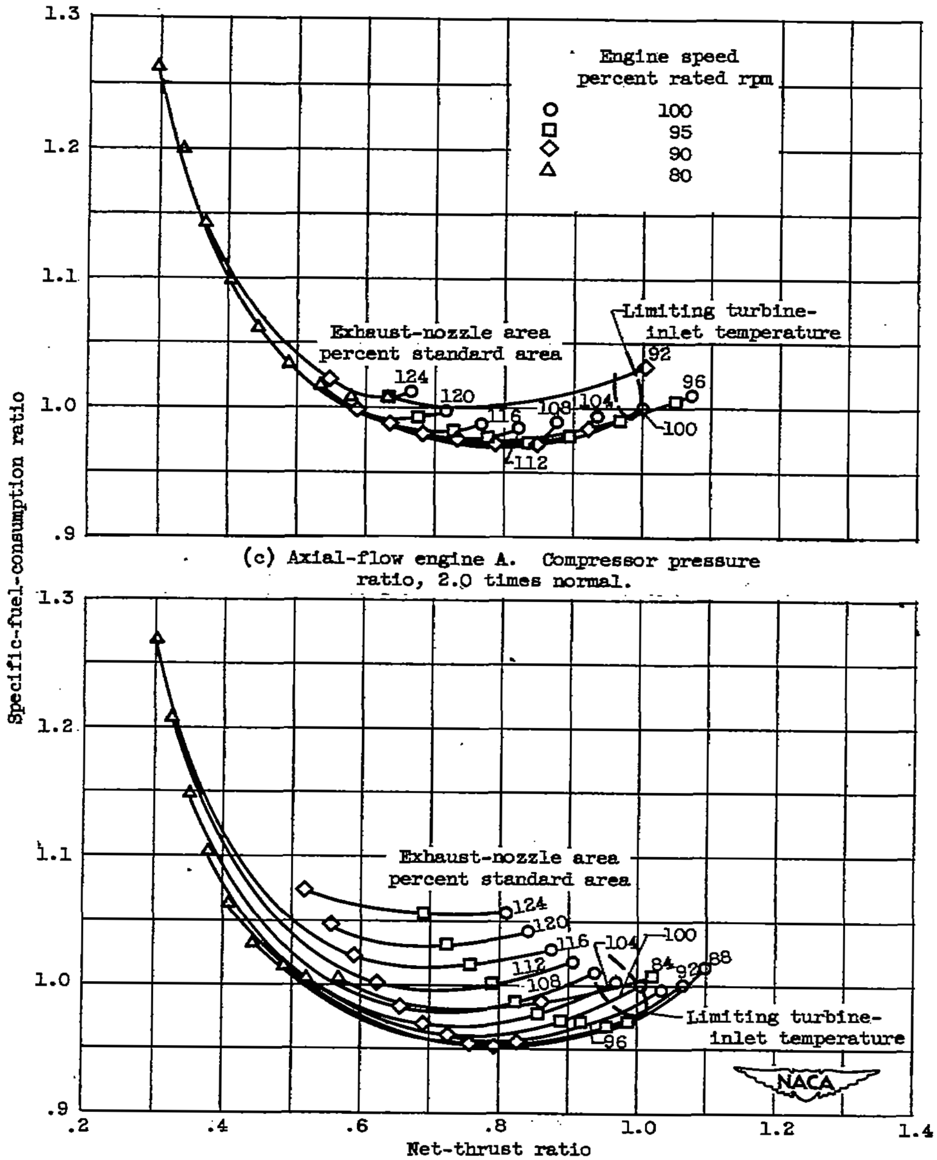
(a) Axial-flow engine A. Compressor pressure ratio, 1.5 times normal.



(b) Centrifugal-flow engine B. Compressor pressure ratio, 1.5 times normal.

Figure 5. - Effect of variable-area exhaust nozzle on performance of engines having increased compressor pressure ratio. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

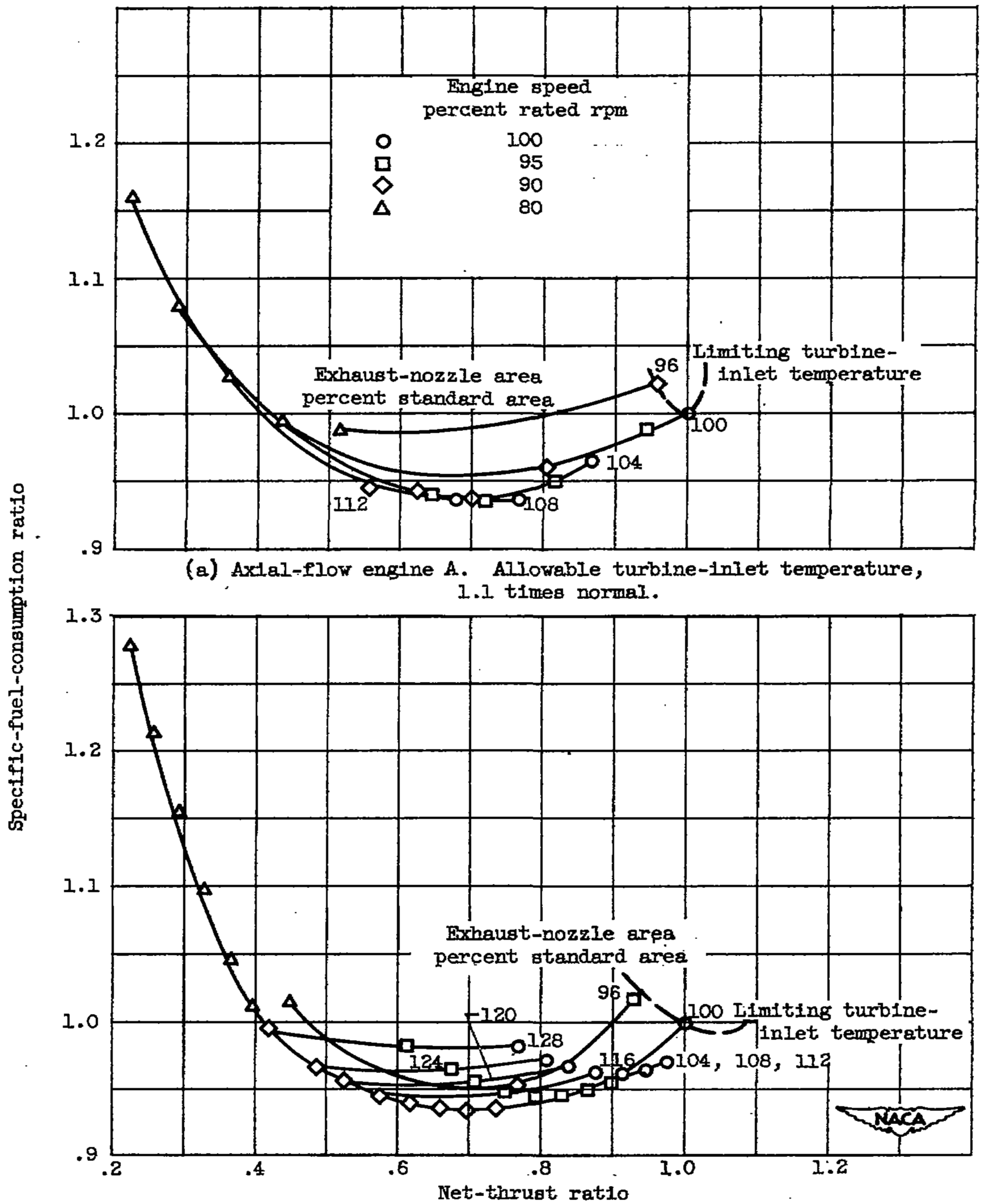
2521



(c) Axial-flow engine A. Compressor pressure ratio, 2.0 times normal.

(d) Centrifugal-flow engine B. Compressor pressure ratio, 2.0 times normal.

Figure 5. - Concluded. Effect of variable-area exhaust nozzle on performance of engines having increased compressor pressure ratio. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).



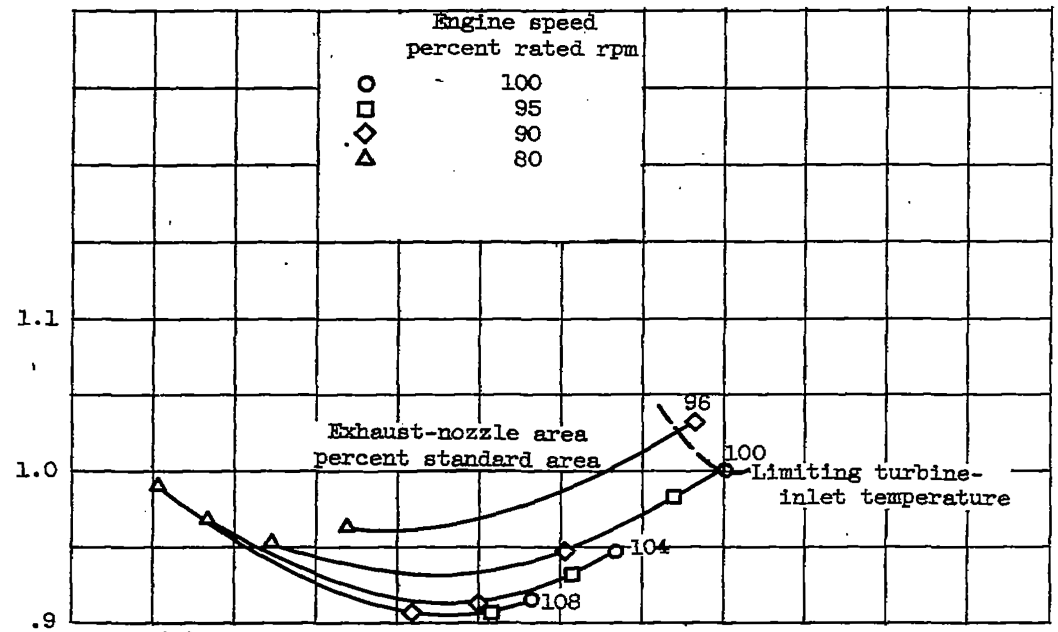
(a) Axial-flow engine A. Allowable turbine-inlet temperature, 1.1 times normal.

(b) Centrifugal-flow engine B. Allowable turbine-inlet temperature, 1.1 times normal.

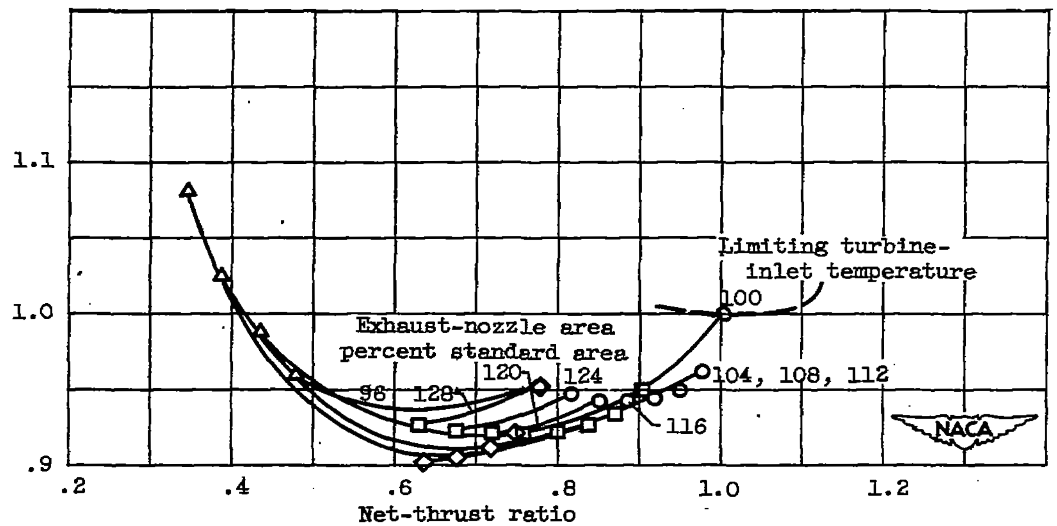
Figure 6. - Effect of variable-area exhaust nozzle on performance of engines having higher allowable turbine-inlet temperatures. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

[redacted]

2521



(c) Axial-flow engine A. Allowable turbine-inlet temperature, 1.2 times normal.



(d) Centrifugal-flow engine B. Allowable turbine-inlet temperature, 1.2 times normal.

Figure 6. - Concluded. Effect of variable-area exhaust nozzle on performance of engines having higher allowable turbine-inlet temperatures. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

2521

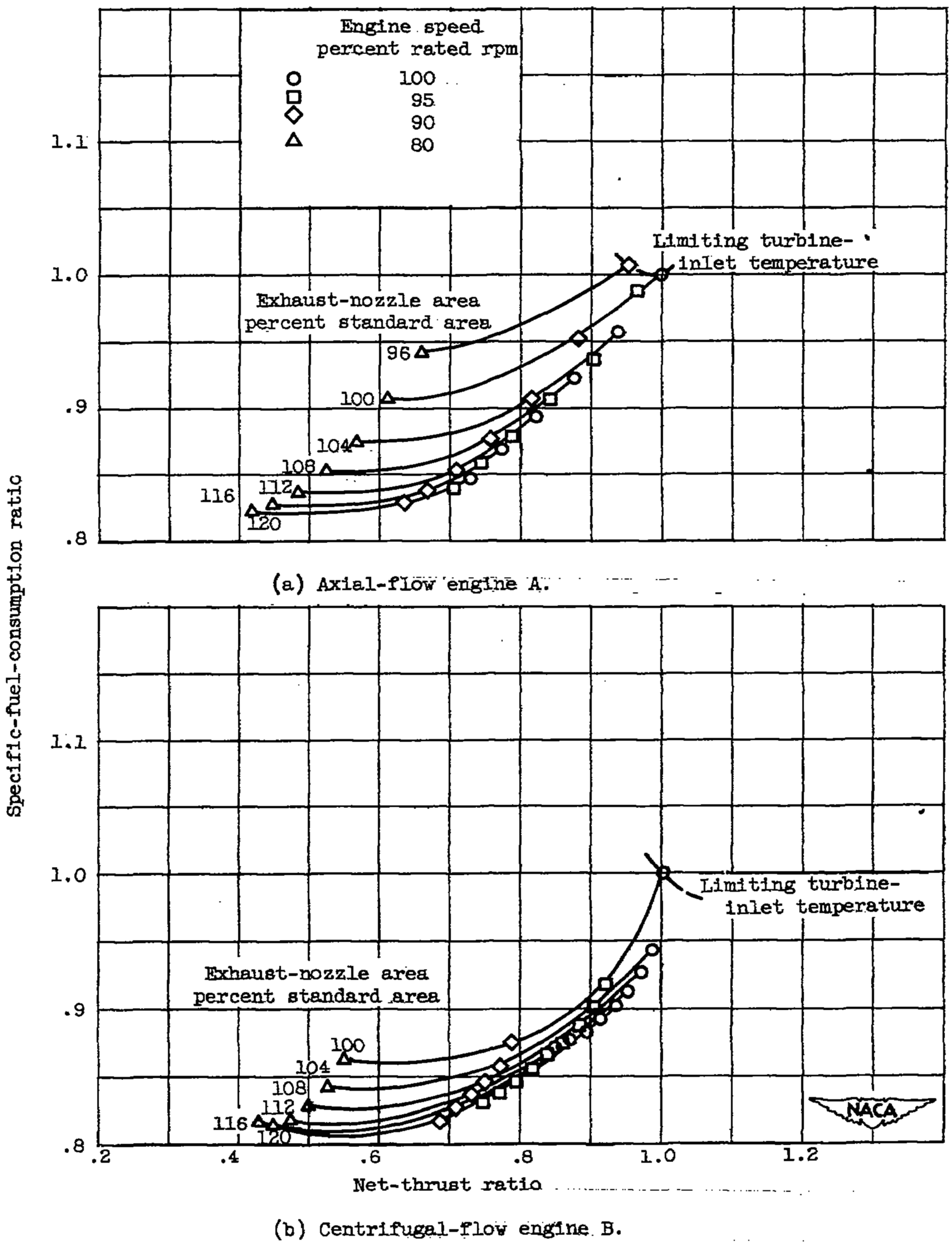


Figure 7. - Effect of variable-area exhaust nozzle on performance of engines having improved compressor and turbine efficiency, increased compressor pressure ratio, and higher allowable turbine-inlet temperature. Altitude, 30,000 feet; ram-pressure ratio, 1.30 (Mach number, 0.62).

[redacted]

SECURITY INFORMATION

[redacted]

[redacted]